Gapp Progress Report
Year Two GC04-147a
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Title: Integrated Modeling of Snow, Soil Moisture, Groundwater, and Lake-Levels for Long Range Forecasting of Water Resources in the Great Salt Lake Basin

Project Duration: 05/01/2004 - 04/40/2007

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Institution: Penn State University, Northwest Watershed Research Center, USDA-ARS

Introduction: This research is developing a multi-scale integrated model for water and energy in the mountain-front setting of the Wasatch-Great Salt Lake (W-GSL) system in north-central Utah. The watershed is within the Great Basin Physiographic province of the western US. The W-GSL basin is forced by snowmelt, recharge, streambed recharge, and evaporation-transpiration. The water and energy balance changes dramatically across the mountain-front. That is, mountain precipitation exceeds annual evapotranspiration $P > E$, and on the valley floor $P \leq E$. The integrated model for the Great Salt Lake Basin utilizes the new Penn State Integrated Hydrologic Model (PIHM) (Qu and Duffy 2005), a new subroutines for a 2-layer snowmelt model (Marks, 2002), and lake level-area-volume model is currently under development. A major focus of research this year was the development of a "domain decomposition tool" that efficiently discretizes the basin into elements over which the equations of motion can be solved. Our strategy is to use a nested approach. That is, we have resolved the overall basin with a relatively coarse grid and then embeded a high resolution domain for detailed water budget analysis internally, similar to the GCM-Meso-Scale climate models. Example grids for low- and high resolution models are given in the Results section below.

An experimental "total-flux" array is being developed at nearby Reynolds Mountain watershed for integrated cold- and warm-season observations of local groundwater flow, infiltration-recharge, snowmelt, evaporation, and transpiration. The array was partially installed with above- and below-canopy eddy flux tower in the Fall 04. Observation wells were installed, but deeper wells will be installed this spring to complete the array during late '05 or spring' 06.

Project Goals/Objectives: The basic hypothesis of the research is: *The water cycle within topographically and hydrologically-closed landforms of the Great Basin represent a multiscale averaging and amplification of the regional climate signal. The dominant time scales of the output (streamflow and lake level) are determined by the space-time scales of storage within the mountain and basin system. Recently identified thresholds, feedbacks and nonlinearities in mountain-front stream-aquifer-lake system serve to amplify low-frequency modes in atmospheric forcing (Duffy, 2003) causing relatively* *weak climate oscillations to become dominant modes within the basin through a mechanism of stochastic resonance, or noise-induced (e.g. weather) amplification. That is, the Great Salt Lake is dominated by interannual to decadal fluctuations. This so even though the Wasatch mountain's receive up to 600 inches of snow per year, and there are no glaciers. So where do these long time scales come from (see Figure 1a-b)?*

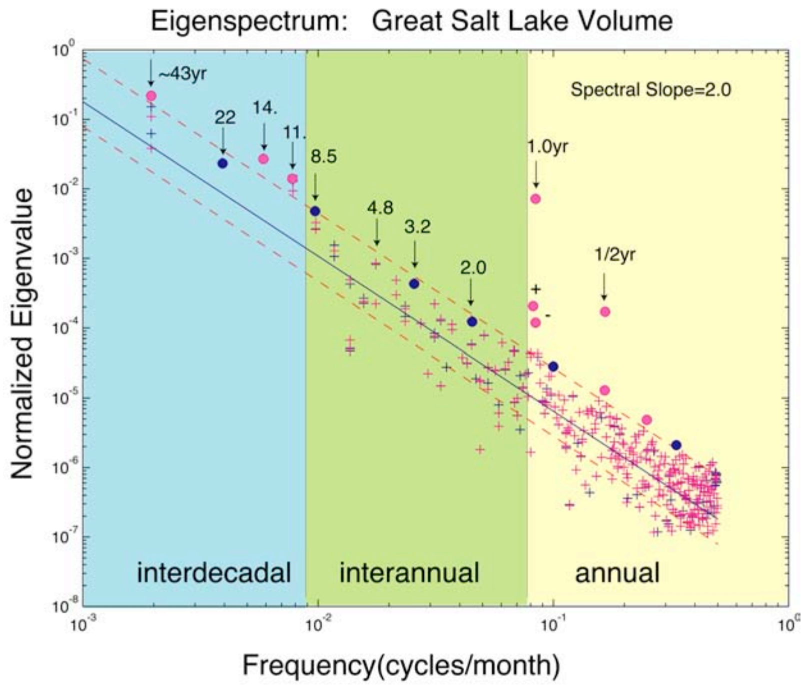


Figure 1a.The Great Salt Lake eigenspectrum estimated from the observed lake volume record 1847-1997. Note the power-law behavior of the low-frequency oscillations (spectral components with frequency $f < 0.083$ cycles/month (period >12 months).

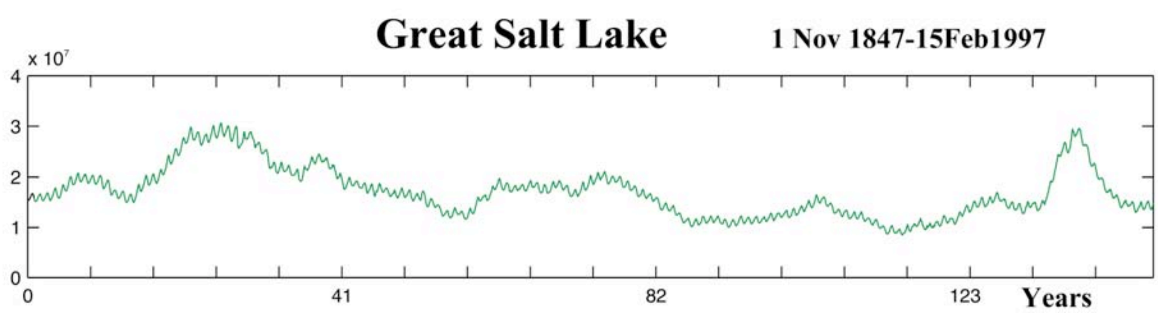


Figure 1b. The recorded time series (1847-1997) of the Great Salt Lake volume. Note the importance of long-term decadal oscillations in this case.

The research will test this hypothesis and show how natural variability of closed-basin response to climatic fluctuations from random, seasonal, interannual, interdecadal and longer oscillatory components may interact with the time scales of deep soil-moisture and groundwater storage to amplify low-frequency modes in runoff and lake levels.

Results and Accomplishments

Model Development & Domain Decomposition: The hydrological processes included in the model are: tree canopy and low-vegetation interception, precipitation (rain and snow), evapotranspiration, overland flow, lake or reservoir storage, infiltration, vertical unsaturated flow, lateral groundwater flow, surface flow and channel routing. All of these processes are now implemented in PIHM as of 2005. PIHM uses a Triangular-Irregular Network (TIN) representation of the watershed discretization, and formulates the governing equations using the semi-discrete finite volume method (Qu and Duffy, in review) with an efficient and accurate solver for the system of dynamical equations. The TIN for the Wasatch-Great Slat Lake Basin (WGSLB) is generated from the digital terrain model and the river network at a user specified resolution (see Results below)

Table 1 provides a list of the physical processes in the model including several options for climatic forcing. Of particular importance to this research is the ability to have fully coupled-lake-groundwater interaction. Because of the multiple time scales in a multi-process model, the resulting system is likely to be "stiff". That is, one or more processes may have very small time constants in the system. For stiff systems, it is necessary to use implicit ODE solvers which require more operations in one time step to meet numerical stability criteria [Ascher and Petzold, 1998]. In general, the semi-discrete finite volume approach is a flexible and efficient strategy for multi-process hydrologic modeling, and each algorithm has been tested to give comparable results to existing finite difference and finite element codes [see Qu and Duffy, in rev., Abbott et al., 1986].

Table 1. The coupled processes included in PIHM, including the status of each implementation and those that will be included in this study (** indicates this study).

Process	Theory/Source	Implementation			Reference
		2004	2005	2006	
Channel flow	1-D Diffusion eq	*			Sleigh et al. [1998]
Overland flow	2-D Diffusion eq	*			Sleigh et al. [1998]
Unsaturated flow	1-D Richard's eq	*			Duffy [2004]
Groundwater	2-D Boussinesq	*			Duffy [2004]
Lake-Wetland	Lake-wetland-groundwater	**	**		Merritt and Konikow [2000]
Sediment Transport	Bedload		*	*	Under development
	Suspended		*	*	Under development
Snow	Temp-Index	**			Brubaker et al. [1996]
	Radiation-based		**	**	Anderson [1976]
Evapotranspiration	Radiation-based		**	**	Priestly-Taylor [1972]
	Temp-Based	**			Hammon [1963] , Dingman [2002]
Dynamic Energy Bal.	Cold/Warm Season		**	**	Anderson [1976]
Vegetation Model	cohesion theory		*	*	under development
Atmospheric Forcing	Stat. Downscaling		**	**	Hay et al, [2000]
	NCEP-LDAS	*	**	**	Mitchell, 2003

The User Interface and Geodatabase for the W-GSL

The large amount of spatial and temporal information involved in water resources prediction makes GIS a powerful tool in support of modeling. An important decision of PIHM model development was to include a seamless hydrologic pre- and post-processing prototype using an object oriented approach. A single geodatabase is utilized for model parameter estimation and space-time visualization. The Modular Modeling System (MMS) of the USGS is presently being implemented to provide the pre- and post processing step for PIHM (http://wwwbrr.cr.usgs.gov/mms/). Our main task here (Fig 2) is to implement MMS along with the ARC_HYDRO GIS tools of Maidment (2002) into a seamless interface for model support and visualization. The final step will be to integrate the data handling, model development, solver and output results as a seamless or single user interface. We note that a-priori parameters, included in the pre-processor (geodatabase) step are presently being collected for the WGSLB, and this task should be completed by Jan-Mar 2006.

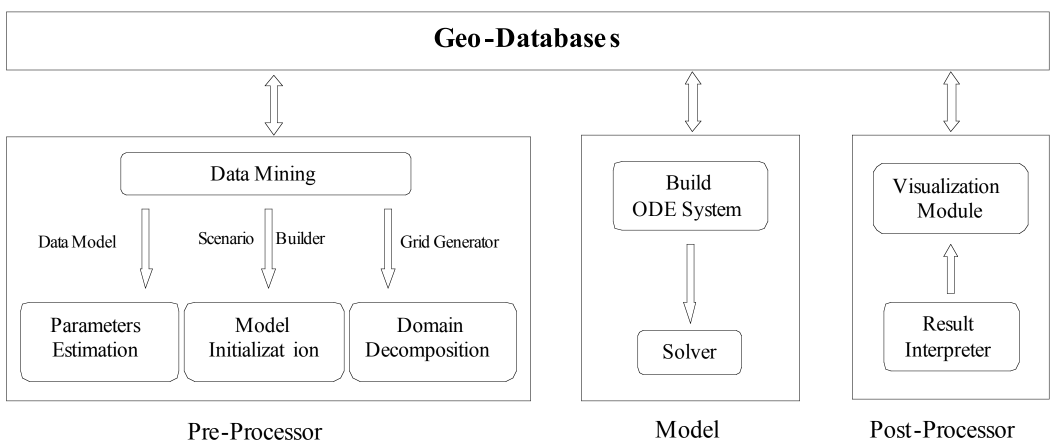


Figure 2 Schematic view of a seamless hydrologic modeling system.

The modeling strategy relies on GIS data layers for all inputs to the integrated model including: delineation of watershed boundaries and/or model hydraulic boundaries, recharge patterns, topography, soils, geology, water table, depth of active flow, aquifer properties, etc. Our approach is to form a multi-scale dynamic water budget using an approximation to the fully-coupled equations of motion for surface and subsurface flow forced by atmospheric inputs and snowmelt. Details of the integrated model are described in a later section. Table 2 is listing of the necessary model data sets and the coarse-resolution GIS database currently acquired for the W-GSL watershed. The low-resolution model is our first implementation of the integrated model (2005) and will provide initial estimates of snowmelt and recharge across the basin and initial conditions for high-resolution simulations for year 3.

Validation sites have been established within the USDA-ARS Reynolds Creek Experimental Watershed. A small snow-dominated headwater catchment (0.4 km^2, 2024 – 2139 m) has been instrumented for detailed monitoring of snow thermal and mass, soil moisture, groundwater and streamflow conditions, including 9 micro-meteorological stations, 4 snow energy balance EB sites, and an ETRS system. A larger catchment (1.8 km^2, 1488-1868 m) located within the rain-snow transition zone, spans a greater elevation range. It is instrumented with three primary micrometeorological stations (top, mid, and base) with a connecting transect of temperature and humidity measurement sites allowing us to collect detailed measurements on how moisture and temperature lapses within the Great Basin region. These two intensely instrumented catchments will provide information for scaling processes and precipitation form and distribution using a combination of station and remote sensing data from the detailed catchment scale to larger areas within the Great Basin.

Category	Data Sets	Type	Characteristics
Climate	P, T_{min}, T_{max} SR, SR_i, RH, P_{vap} PET, AET, W	Point Point Point	Monthly, daily, 6-hr; 1/8° grid; Monthly, daily , 6-hr ; 1/8° Monthly, daily, 6-hr ; 1/8° grid;
Vegetation	VGVT, LAI, LAIW	Point	Monthly, daily; 1/8° grid;
Topography	z_{gs}	Grid	Grid; 1/3 arc second (~10m)
Streams	Name, HUC, FlowDir Name, Q, DA, W, D ID, FlowDir, Order, DA	Line Point Line	1:24,000 scale Spatially distributed; hourly-daily Grid; 1/3 arc second; calculated from topography grid
Waterbodies Reservoirs	Name, HUC Name, SA, DA, SV_{norm}, SV_{max}	Polygon Point	1:24,000 scale Spatially distributed; 1:2,000,000 scale
Soil	Name, PermH, PermL, RockDepH, RockDepL	Polygon	1:24,000 scale (SSURGO)
Physiography	Province, Age, Section, Glaciation	Polygon	1:250,000 scale
Hydrogeology Wells	FM, Age, RockTyp FM, Section, K_{sat}, D, n_p ID, Alt, Levels	Polygon Table Point	1:24,000 scale Compiled measurements Spatially distributed; Compiled measurements
Conceptual model	All of the above.	Figures, Tables, Text	Compiled summaries, concepts, and measurements

Table 2: This table lists the preliminary GIS data/parameters for the Wasatch-Great Salt Lake basin to be used for the low-resolution model. Year 2 will see extensions to this database with higher resolution as available.

Statistical Downscaling

Statistical downscaling used in this work is a regression-based procedure to downscale atmospheric model output or point climate data for use as input to the distributed watershed models. For the temperature-index model approach (Table 1), point values of daily precipitation and temperature from atmospheric-model output or climate stations are spatially distributed across a basin using the method of Hay et al. (2000). The approach uses multiple linear regression relations developed for each dependent climate variable. The independent variables are the measurement station latitude (x), longitude (y), and elevation (z). Minimum data requirements for daily model runs include daily precipitation and maximum and minimum air temperature. For 6-hourly simulations the same procedure is used to interpolate the NCEP-LDAS climate data products (Table 1), and the energy balance model is used to represent cold and warm season processes (evapotranspiration and snowmelt). The lake-aquifer model component simulates transient stage fluctuations, and will allow drying and wetting of separate lake basins or merging into a single water body as lake-wetland levels rise. Lake-wetland bathymetry is specified through the TIN, although a single water level elevation is used at present.

Our strategy for the scenarios is to use a nested-multi-scale version of PIHM with a relatively coarse-grain solution for the entire watershed, with nested domains of higher resolution in regions where the wetlands exist. The notion is that larger scale model simulations will create boundary and initial conditions for the nested-high resolution domain areas where wetland mapping statistics will be evaluated. The same strategy can be used for drought mapping where falling groundwater levels, streamflow, and soil moisture may cause the lake to recede.

Evaporation-Transpiration-Recharge-Snowmelt (ETRS) ARRAY

This element of the research involves the design and installation of a total-flux array for testing the concept of an integrated flux measurements. We refer to this as an ETRS array (evaporation-transpiration-recharge-snowmelt). Using this experimental setup we are attempting to get a comprehensive evaluation of the relation of snowmelt to recharge and runoff, while at the same time observing the atmospheric and energy and moisture fluxes. The array will allow a comprehensive and coherent set of flux observations of the atmosphere-land surface (snow and vegetation)-subsurface system at a highly monitored site. The use of meteorological flux towers and eddy covariance systems in mountainous regions to estimate evapotranspiration (ET) is complicated by the variable footprint of the observations, where wind speed, wind direction, turbulence and the surrounding terrain, affect the scale of the moisture-flux estimate. This is further complicated for cold season conditions when evaporation from the snowpack occurs under stable atmospheric conditions. For patch-scale research or topographic transects where differences in water use by vegetation type is critical, the impact of the changing atmospheric footprint on estimates of ET is not well understood.

This element of our research involves the development of a new theory and experimental design for the total moisture flux estimation suitable for warm and cold season conditions. The experimental array is located within a fixed, finite volume of soil using concurrent soil moisture, water table, and meteorological sensors. The experimental design requires soil moisture and water table sensor arrays to be deployed at the centroid and boundaries of the soil volume, with precipitation measurements and eddy flux tower positioned centrally within the array. For the model, a local, dynamic water balance is formed by direct integration of Richards equation using a Finite Volume (FV) formulation of unsaturated-saturated moisture storage. The resulting dynamical system is continuous in time, discrete in space. Using field estimates of soil characteristic curves, the dynamical equations are solved numerically. The experiment will show how the theory can be used for optimal sensor design given soil conditions and the optimal estimation of the total flux components within the array. We refer to the total flux measurement system as an ETRS array (Evaporation, Transpiration, Recharge, and Snowmelt).

During the fall 04 and summer of 05 we installed an ETRS array at the Northwest Watershed Research Center, near Boise. The instrumentation package included: eddy flux towers at 2 heights above and below the canopy; snow depth, density, radiation, temperature instrumentation; soil moisture, temperature and soil potential at 3 depths above the water table; an equilateral or finite element array of piezometers with pressure tranducers to estimate the lateral flux of groundwater to the adjacent stream. The installation is not yet complete as observation wells installed this year were not deep enough to cover the seasonal water table fluctuations. Deeper wells will be installed this spring.

The measurement suite, once completed, will be particularly important during periods of very stable winter air masses which can invalidate the eddy-flux estimate, and making alternative flux estimates important for reducing errors from the instruments. During the warm season the ETRS array will allow independent estimation of evaporation and transpiration. We expect to be able to using redundant or multiple flux estimates for improving or reducing the uncertainty in the evaporative flux within the array. Groundwater level observations will allow recharge and the lateral flux of groundwater to estimated within the same finite volume of soil. At present we are still in the process of installing the piezometers as the shallow drilling equipment we have was not able to drill through some of the volcanic rocks at the site. The site will be complete by spring 06.

Figure 3. Eddy-flux tower at the Northwest Experimental Watershed, USDA.

Domain Decomposition

During the second year we have completed the domain decomposition tool and have generated a range of Once the watershed domain-decomposition is complete, each TIN is projected vertically from bedrock through each geologic and soil layer through the canopy to form the finite volume or prismatic element, over which the flow equations are approximated. The model domain-decomposition preserves the channel network and the watershed boundaries. The stream channel cross-section can be trapezoidal, rectangular, or other as shown in figure 4a-b.

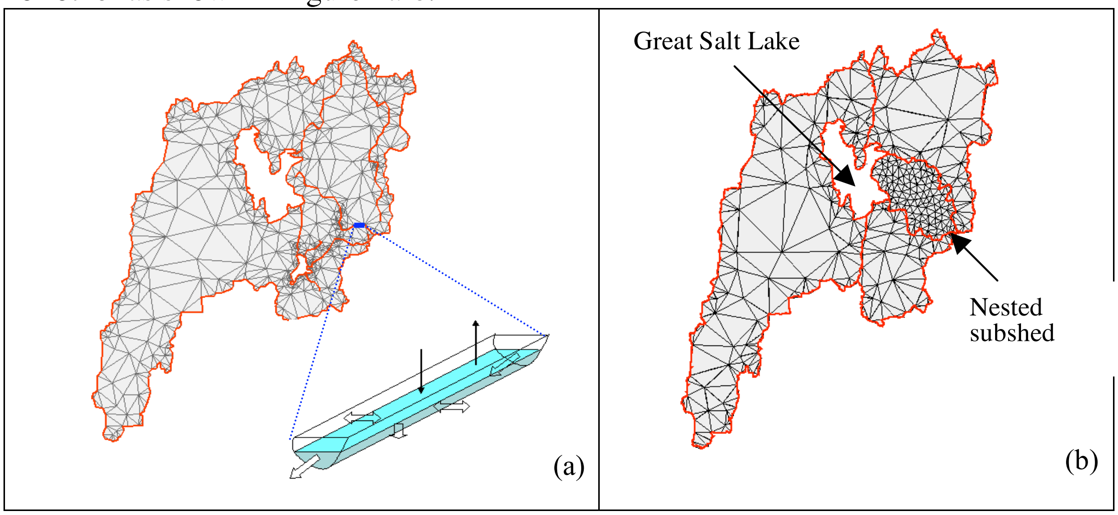


Figure 4 a) The finite volume approach used in PIHM (Penn State Integrated Hydrologic Model uses a TIN (triangular irregular network) to decompose the watershed into elements and projects the TIN downward to form the Finite Volume for modeling. b) Example watershed decomposition into a TIN, shown for the case with a nested high resolution sub-watershed (Weber River) and the Great Salt Lake.

Details of the governing equations, boundary conditions and interactions are discussed in Duffy [2004], [Qu and Duffy, in review]. At present we have generated a relatively coarse grid network for the basin and we are populating the geodatabase for the model at this scale (1b). The model is designed to capture “dynamics”in multiple processes while maintaining the conservation of mass at all cells, as guaranteed by the finite volume formulation.

Signal Processing

Figure 5 (Kumar and Duffy, in-review) gives six examples of P-T-Q reconstruction of low-frequency oscillations (annual, interannual, and decadal) within the Colorado Plateau and Rocky Mountain regions. Average annual oscillations are shown for the first half of the 20th century (pre-1950) and the second half (post 1950). Significant hydrologic changes are observed in each case. The orange trajectory is the pre-1950 annual average and the blue is post-1950. Also shown are the January, May and August point P-T-Q data for each period, indicating how the monthly data has varied over the 20th century.

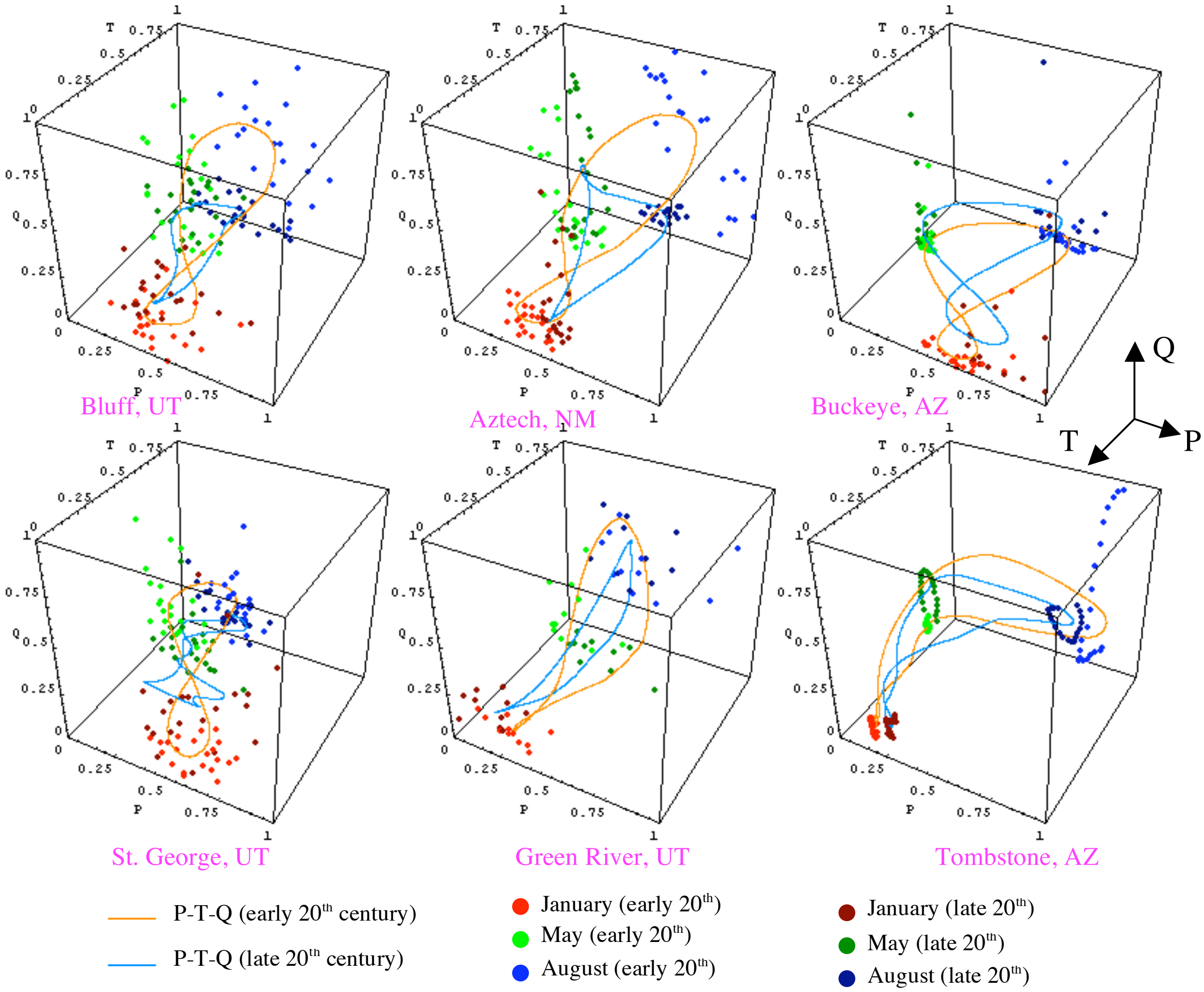


Figure 5. P-T-Q phase-plane trajectory plot for low frequency (annual, interannual and decadal) reconstructed time records showing how the phase-plane has changed from early-to-late 20th century. Q-vertical and, P-T on the horizontal axes.

In most cases the significant hydrologic change that has occurred is not a change in the P-T-Q pattern, but a significant reduction in the runoff (vertical axis) due to human activity. More subtle effects are seen in the Tombstone example where winter precipitation has increased in the late 20th century and a clear climate change impact.

Integrated Modeling

This research is implementing an integrated finite volume model for simulating dynamic/distributed water budget including the estimation of distributed snowmelt, evapotranspiration, recharge, surface runoff, and baseflow. The model is known as PIHM (Penn State Integrated Hydrologic Model) and includes overland flow, unsaturated flow, groundwater flow and channel flow processes (Table 3).

Process	Governing equation	Original governing equations	Semi-discrete form	Approximation
Channel Routing	St. Venant Equation	$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} = q$	$\left(\frac{d\varsigma}{dt} = P_c - \sum Q_{gc} + \sum Q_{oc} + Q_{in} - Q_{out} - E_c\right)_i$	Kinematic or Diffusion wave
Overland Flow	St. Venant Equation	$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = q$	$\left(\frac{\partial h}{\partial t} = P_o - I - E_o - Q_{oc} + \sum_{j=1}^{3} Q_s^{ij}\right)_i$	Kinematic or Diffusion wave
Unsaturated Flow	Richards' Equation	$C(\psi)\frac{\partial \psi}{\partial t} = \nabla \cdot (K(\psi)\nabla(\psi + Z))$	$\left(\frac{d\xi}{dt} = I - q^0 - ET_s\right)_i$	Shallow water table
Groundwater Flow	Richards' Equation	$C(\psi)\frac{\partial \psi}{\partial t} = \nabla \cdot (K(\psi)\nabla(\psi + Z))$	$\left(\frac{d\varsigma}{dt} = q^0 + \sum_{j=1}^{3} Q_g^{ij} - Q_l + Q_{gc}\right)_i$	2-D Dupuit approximation
Interception	Bucket Model	$\frac{dS_I}{dt} = P - E_I - P_o$	$\left(\frac{dS_I}{dt} = P - E_I - P_o\right)_i$	N/A
Snowmelt	Temp Index Model	$\frac{dS_{snow}}{dt} = P - E_{snow} - \Delta w$	$\left(\frac{dS_{snow}}{dt} = P - E_{snow} - \Delta w\right)_i$	N/A
Evapotran-spiration	Pennman-Monteith Method	$ET_0 = \frac{\Delta(R_n - G) + \rho_a C_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})}$	$\left(ET_0 = \frac{\Delta(R_n - G) + \rho_a C_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})}\right)_i$	N/A

Table 3. Major hydrologic process, governing equations, and approximation for PIHM.

The model also includes algorithms for snowmelt and vegetation water use. However, both of these will be improved in this study. PIHM is utilized in this application as a multi-scale, distributed-dynamic water budget for groundwater and surface water in the GSL basin. Table 3 shows the processes, and the original and reduced governing equations. For channel routing and overland flow the kinematic wave and/or diffusion wave approximation will be used. For saturated flow, the 2-D Dupuit approximation is applied. For unsaturated flow a 1-D vertical integrated form of Richards's equation is applied.

The watershed domain decomposition applies Delaunay Triangulation with constraints in 2-D and project it to prisms, as shown in Figure 6. The advantage is that the flux across any edge to its neighbor is always normal to its common boundary by definition. This reduces computational cost to evaluate flux across element boundary. The scope and scale of water resource problems make GIS a powerful tool in developing solutions (Maidment, 2002). In PIHM, geographic information system (GIS) tools are used for domain decomposition, data analysis, pre- and post-processing of data parameters visualization. The unstructured grid used to decompose the domain is referred as triangular irregular network. The TIN is the most efficient way to represent the terrain and meet simulation goals for computational efficiency, constraints on hydrographic points (including hydraulic structure, such as gage stations and dams) or critical terrain points (including local surface maximum/minimum, convexity/concavity, or saddle points), and these are easily accomplished in the GIS tool.

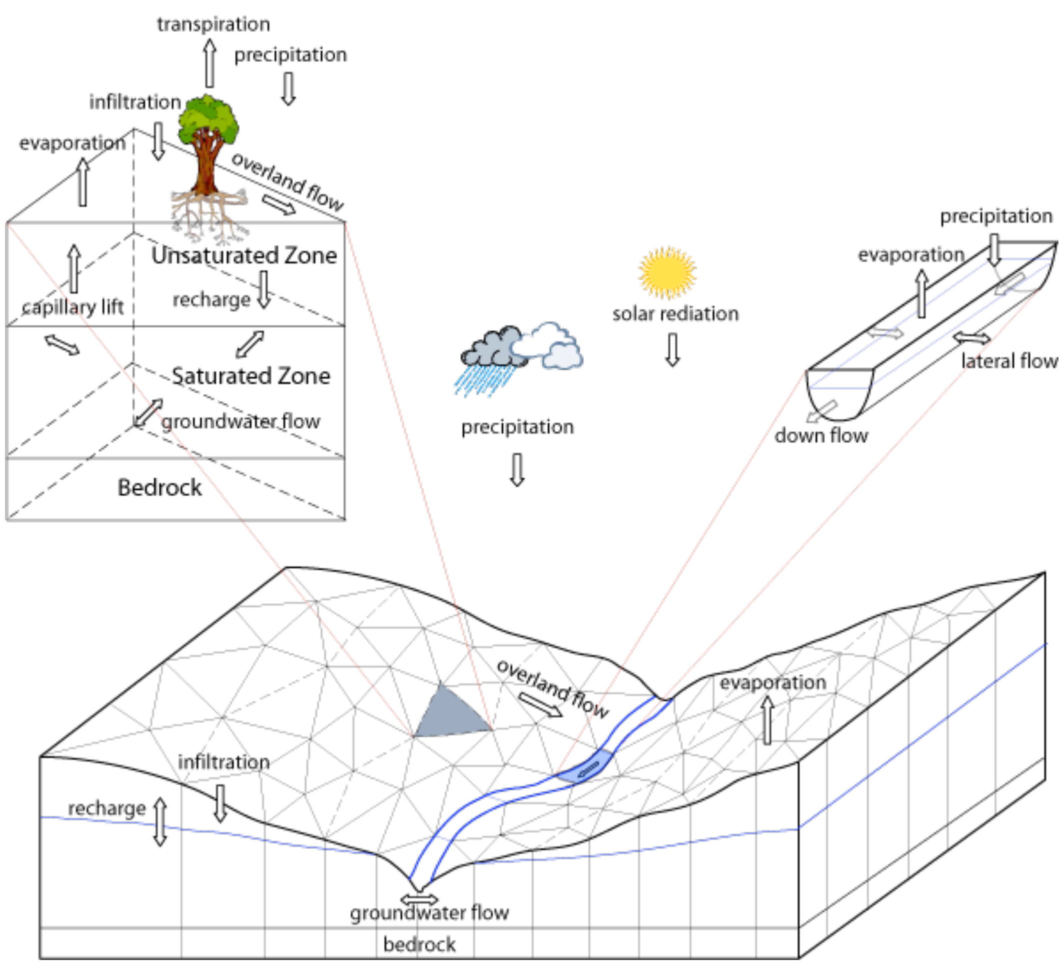


Figure 6 The domain decomposition for PIHM within a stream reach. Each prism element incorporates the multiple hydrological processes listed in Table 2. A channel segment is shown to the right.

Other Accomplishments

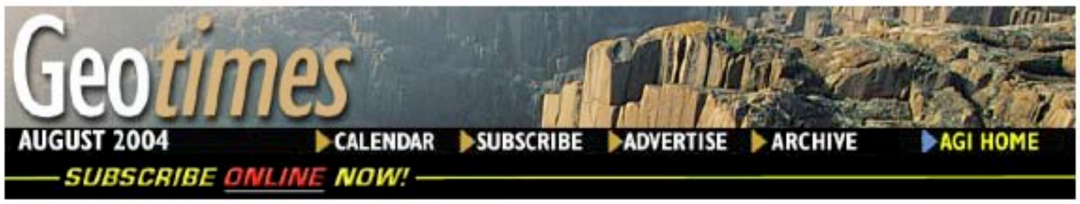
Geological Society of America Salt Lake City Annual Meeting: Oct 15-19, 2005
Chaired the Pardee Symposium:
The Wasatch Range-Great Salt Lake Hydroclimatic System

Christopher J. Duffy, Pennsylvania State University, University Park, Pa.; **Danny Marks**, Agricultural Research Service, U.S. Department of Agriculture, Boise, Idaho; **David G. Tarboton**, Utah State University, Logan, Utah; **Craig B. Forster**, University of Utah, Salt Lake City, Utah

Sponsor: GSA Hydrogeology Division; International Association of Hydrogeologists/US National Chapter; American Geophysical Union (pending final Executive Committee approval)

Symposium Description: The Wasatch-Great Salt Lake Basin forms a microcosm of the global water cycle; its water balance is driven by regional-scale natural and human impacts in a system forced by global weather, regional climate, and local land use. Topographically and hydrologically, the region is a "closed system"; no rivers leave the region, and the water cycle is balanced solely by precipitation and evaporative exchange with the atmosphere. This closed mountain and basin system has the effect of "amplifying" the climate signal through orographic forcing in the mountain range, where most of the precipitation occurs as snow, and through evaporative losses and feedback in the distant arid lake basin. The simplicity of this water balance is a geological marvel, yet complex dynamics between orographic precipitation, vegetation growth (evapotranspiration), streamflow, and mountain-front groundwater flow make a full accounting of the water cycle elusive. Indeed, the precise physical mechanisms, feedbacks, and time scales of mountain-front hydroclimatology, groundwater recharge, and lake dynamics are still in many areas speculative, and the subject of current scientific debate and active research. Integration of these sciences into a comprehensive management tool for prediction and forecasting of water resources availability remains an unrealized goal, due in part to climate variability and human intervention in the water cycle. Redistribution of water resources for exploitation of dissolved salts places additional pressure on the hydrosystem/ecosystem of the Wasatch Range-Great Salt Lake. The economic reserves of this hydroclimatic system, considering the salt industry as well as consumptive use for urban development and crop production, are today vast. Yet the impact of future climatic fluctuations on human activities in the basin could be profound, and overwhelm what is today perceived as an infinite resource. In this session, we convene a broad spectrum of scientists to review the state of our understanding of this prototypical mountain-and-basin system. Presentations will span the disciplines of climate, geology, geochemistry, hydrology, and ecology. Legal perspectives on resource management as well as historical context from the recent geologic past will support discussion about future impacts on the region, both natural (climate and hydrology) and anthropogenic (policy). This session will be aimed at an audience of anyone who is interested in how future fluctuations in climate and hydrology will shape the activities of man in the Great Salt Lake basin.

Mountain-Front Recharge in the News



News Notes

Hydrology

New water model for Southwest

The Rio Grande is living in the 1950s. According to a new model by a researcher working in the New Mexico water basin, the seven-year drought that affected the area in the 1950s may finally be making its way into the Rio Grande. The model might help regional managers adjust water budgets for the dry river basin, with potential applications to other arid systems in the West.

Christopher Duffy, a hydrologist at Pennsylvania State University, pulled together three disparate blocks that make up a typical mountain-river hydrologic system in the arid western United States: recharge (in the high mountains), transport (through fractured rock, aquifers and surface alluvial fans) and release (the river itself). The model uses data and observations for each section, including the input of rain and snow and the rock types and fracture zones. Duffy also took into account water withdrawals from the Rio Grande by river vegetation, plus the evapotranspiration of plants and evaporation of water on the alluvial slopes (the fan-shaped deposits of loose rocks and sediments from streams coming out of the mountains).

After running the numbers, Duffy calculated that the base-level water flow of the Rio Grande is determined by wet or dry climate conditions that occurred 50 years before. From wet years, he could track "a mound of water that takes a long time to get to the river," he says, moving through the system like a wave as it hypothetically propagates through the pores and fractures in the rocks. Evapotranspiration at the river corridor level is "a major loss of water," Duffy wrote in a publication of the model earlier this year in an American Geophysical Union (AGU) monograph. Duffy also presented the model in May at the AGU Joint meeting in Montreal.

"There's a great deal of transferability in this modeling approach because it can be adapted for other arid western U.S. basins," says Michelle Walvoord, a hydrologist at the U.S. Geological Survey in Lakewood, Colo. Although the concept of lag-time responses in river systems is not new, Duffy's "cutting-edge" model is a step forward in incorporating data with "a solid hydrologic conceptual framework," Walvoord says. The model can respond to a variety of hypothetical environmental changes over fairly complex terrain, and over different scales in time and space.

Aside from the quantitative advances in the model, says Cliff Dahm, an ecosystems ecologist at the University of New Mexico in Albuquerque, Duffy's connection of the three blocks of the Rio Grande basin is "the most unique part" of his work. "Nobody that I know of has taken those three pieces and linked them into a hydrological model," Dahm says. The ability to determine lag effects in similar regions has "interesting implications for management" of future water budgets for the Sierra Nevada and off the highlands of the Rocky Mountains, where hydrologic systems feed the Platte, Missouri and other rivers, he says.

Duffy incorporated Dahm's riparian plant evapotranspiration research, and the scientists are now working together to further perfect the three-part model.

Future Work, 2006

The year 3 investigation will complete development of the spatially-distributed water budget (recharge, evapotranspiration, baseflow, surface runoff, snowmelt) for the low resolution model. We are populating the digital database and this should be complete during early 2006, including updated land cover maps, long-term national climatic database products for low-resolution climatic data for the observation record. The investigation will use existing digital GIS hydrogeologic, physiographic, climatic and landuse data to support the model development. Simple optimization tools will be used in the watershed calibration step to improve on the a-priori model parameters. In year 3 we will also focus on calibration of the integrated model, at multiple resolutions, as part of Mukesh Kumar's PhD dissertation. Several papers are under development in this work, including the domain decomposition tool, the utility of the MMS modeling System as a pre- and post-processor, and scenario development for long-term forecasts of the surface- and groundwater resources of the W-GSL system. The first product of this research is a multi-resolution basin-scale reconstruction of closed-lake level fluctuations, soil moisture, groundwater levels and streamflow over a 25 and 50 years period. The second product will be analysis of the NCEP/LDAS products as forcing for long range water resource forecasting with a micro-scale nested subwatershed (Weber River).

Publications from this Project

Journal Publications

Garen, D. C. and **D. Marks**, 2005. Spatially distributed energy balance snowmelt modelling in a mountainous river basin: Estimation of inputs and verification of model results, *Journal of Hydrology* (in press).

Hardy, J.P., **D. Marks**, R. Melloh, G. Koenig, A. Winstral, J. Pomeroy and T. Link, 2004. Solar radiation transmission through conifer canopies, *Journal of Agricultural and Forest Meteorology*, **126**: 257-270.

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